US005961362A

United States Patent [19]

Chalamala et al.

[11] **Patent Number: 5,961,362**

[45] **Date of Patent: Oct. 5, 1999**

[54] **METHOD FOR IN SITU CLEANING OF ELECTRON EMITTERS IN A FIELD EMISSION DEVICE**

[75] Inventors: **Babu Chalamala**; **Arthur J. Ingle**, both of Chandler; **Charles Rowell**, Tempe; **Thomas L. Credelle**, Phoenix, all of Ariz.

[73] Assignee: **Motorola, Inc.**, Schaumburg, Ill.

[21] Appl. No.: **08/927,367**

[22] Filed: **Sep. 9, 1997**

[51] **Int. Cl.**^{6} **H01J 9/38**

[52] **U.S. Cl.** **445/59**

[58] **Field of Search** 445/59, 9, 10, 445/16; 313/309, 336, 351, 495

[56] **References Cited**

U.S. PATENT DOCUMENTS

3,822,086	7/1974	Palk	316/28
5,442,255	8/1995	Ise et al.	313/495
5,763,998	6/1998	Colombo et al.	313/495

Primary Examiner—Nimeshkumar D. Patel
Assistant Examiner—Michael J. Smith
Attorney, Agent, or Firm—S. Kevin Pickens

[57] **ABSTRACT**

A method for in situ cleaning of electron emitters (**126, 226, 326, 526**) in a field emission device (**100, 200, 300, 400, 500**) includes the steps of controllably providing hydrogen gas (**142, 242, 342, 542**) within the field emission device (**100, 200, 300, 400, 500**) at a time during the operational life of the field emission device (**100, 200, 300, 400, 500**) and, thereafter, emitting electrons from the electron emitters (**126, 226, 326, 526**), thereby forming hydrogen free radicals, which decontaminate and condition the emissive surfaces of the electron emitters (**126, 226, 326, 526**).

21 Claims, 3 Drawing Sheets

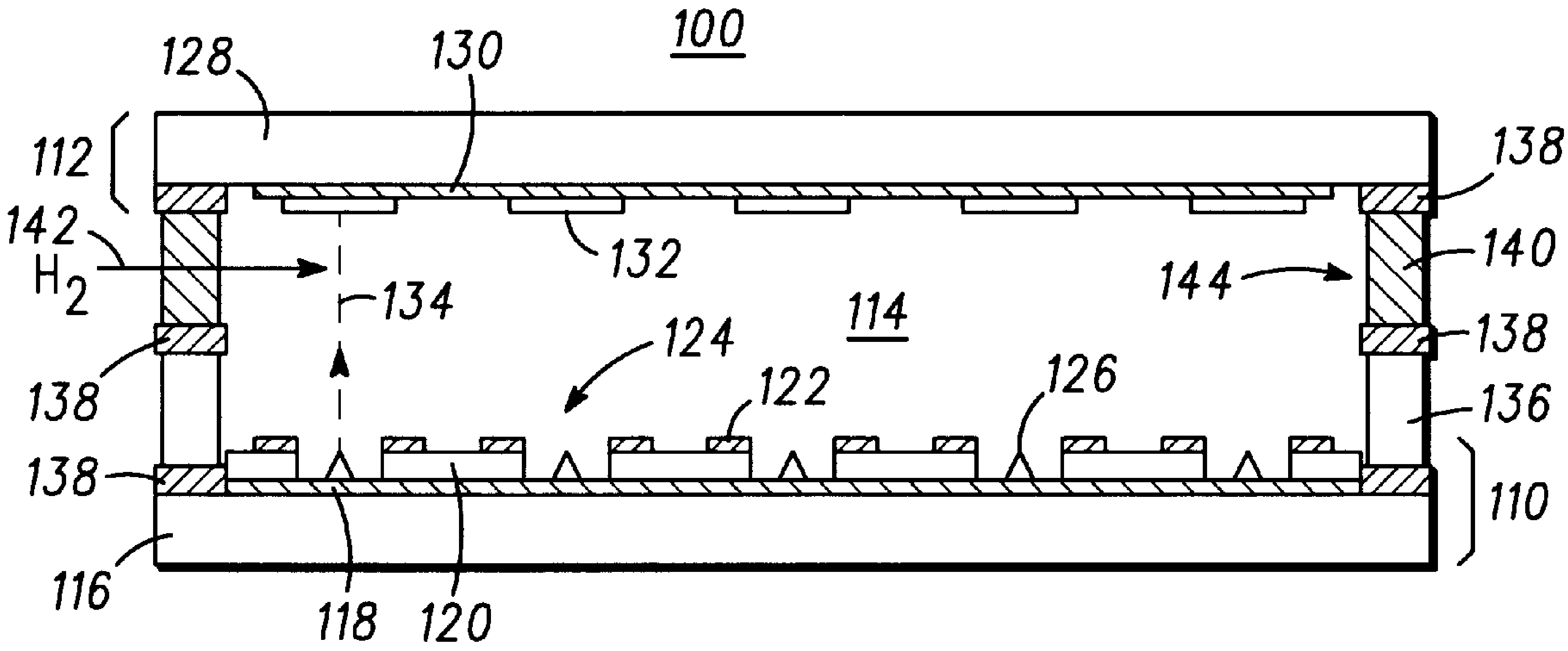


FIG. 1

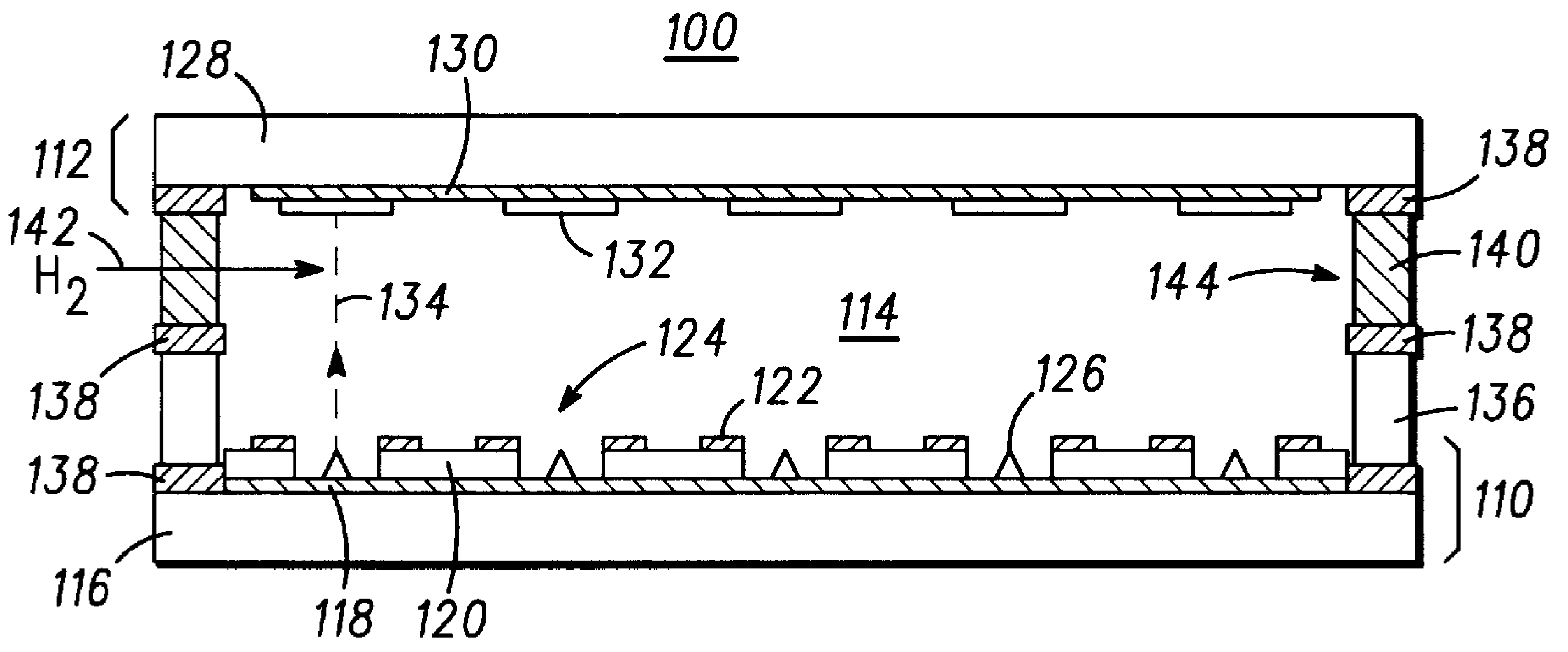


FIG. 2

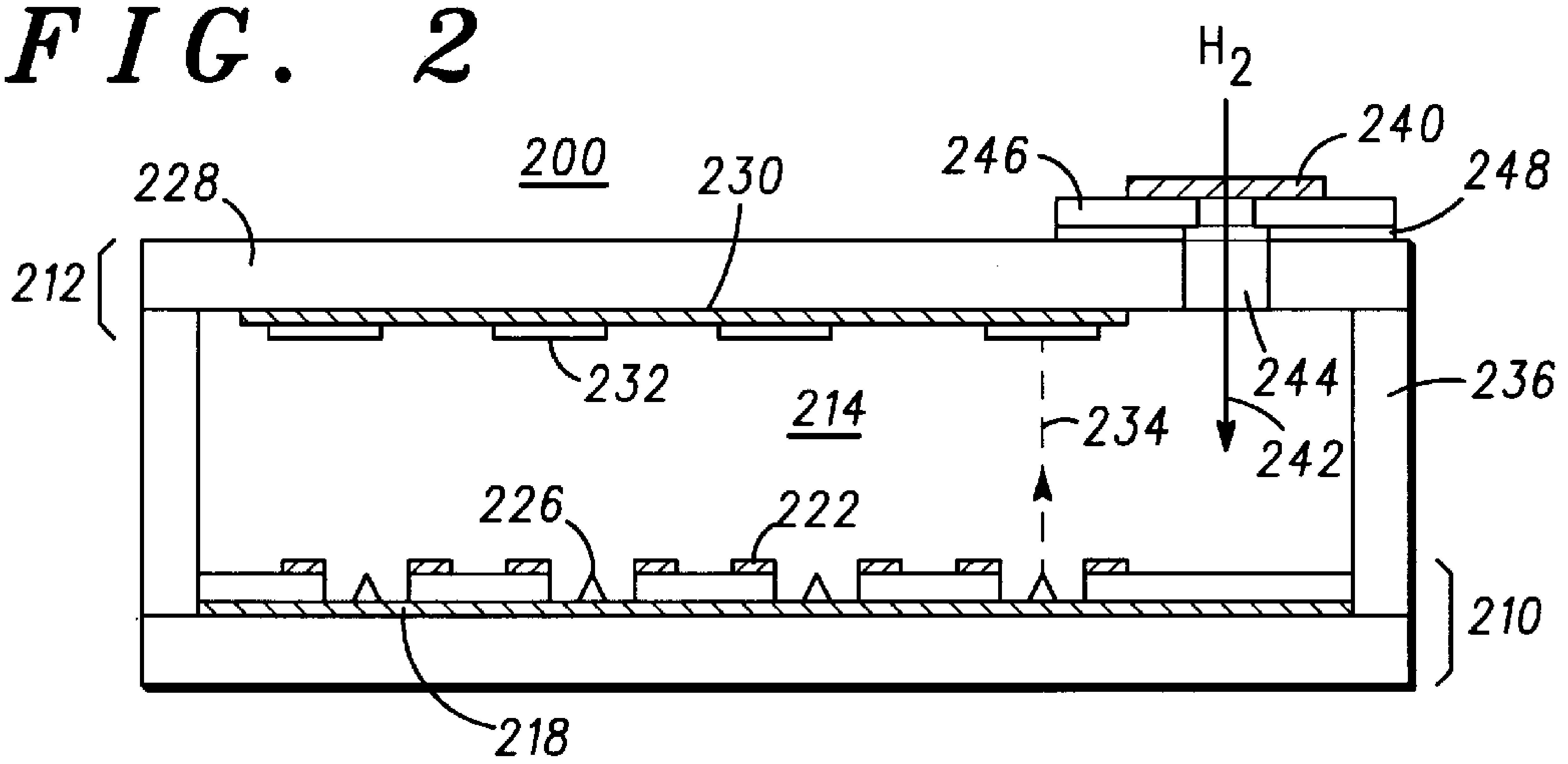
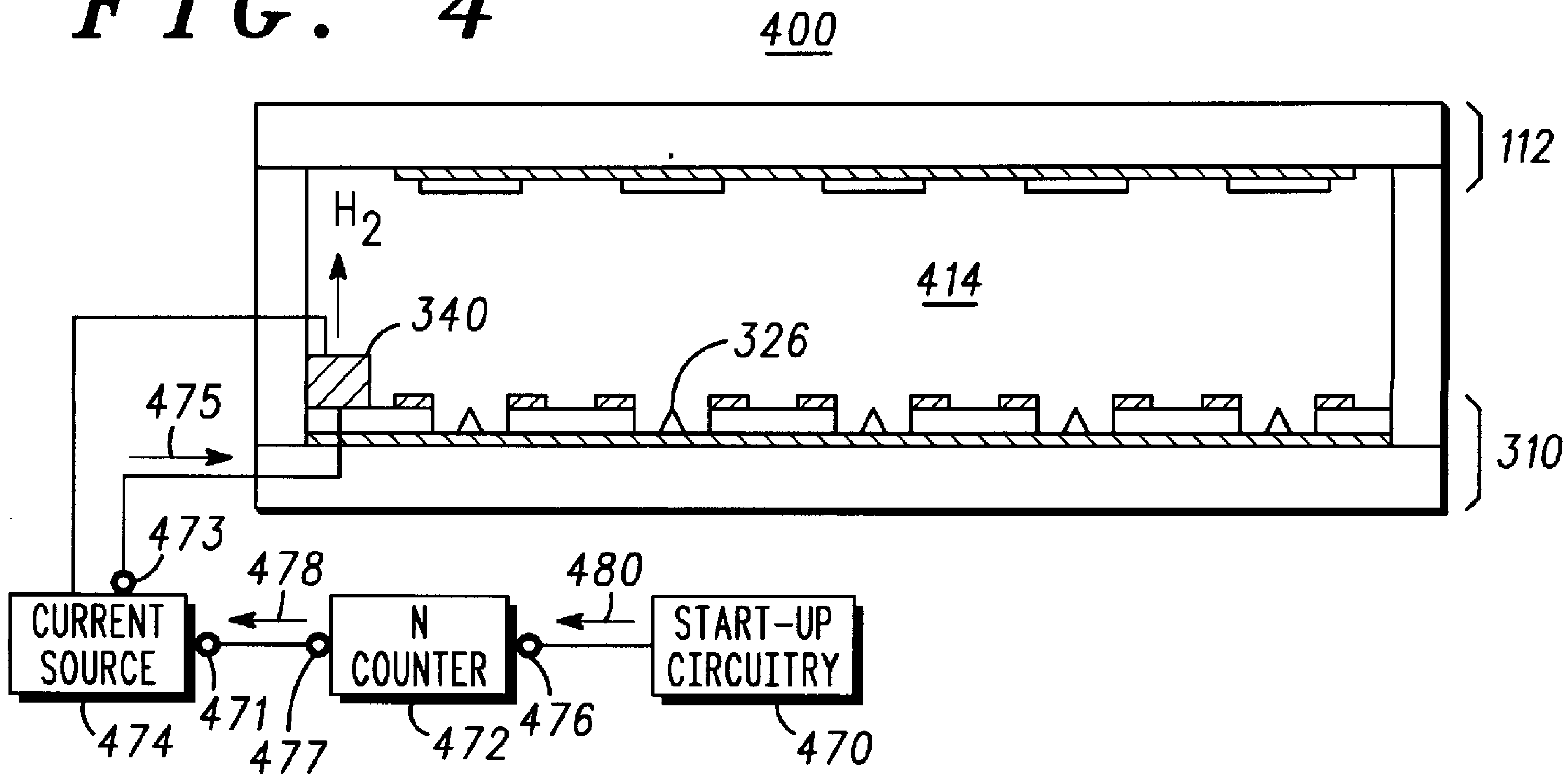


FIG. 4



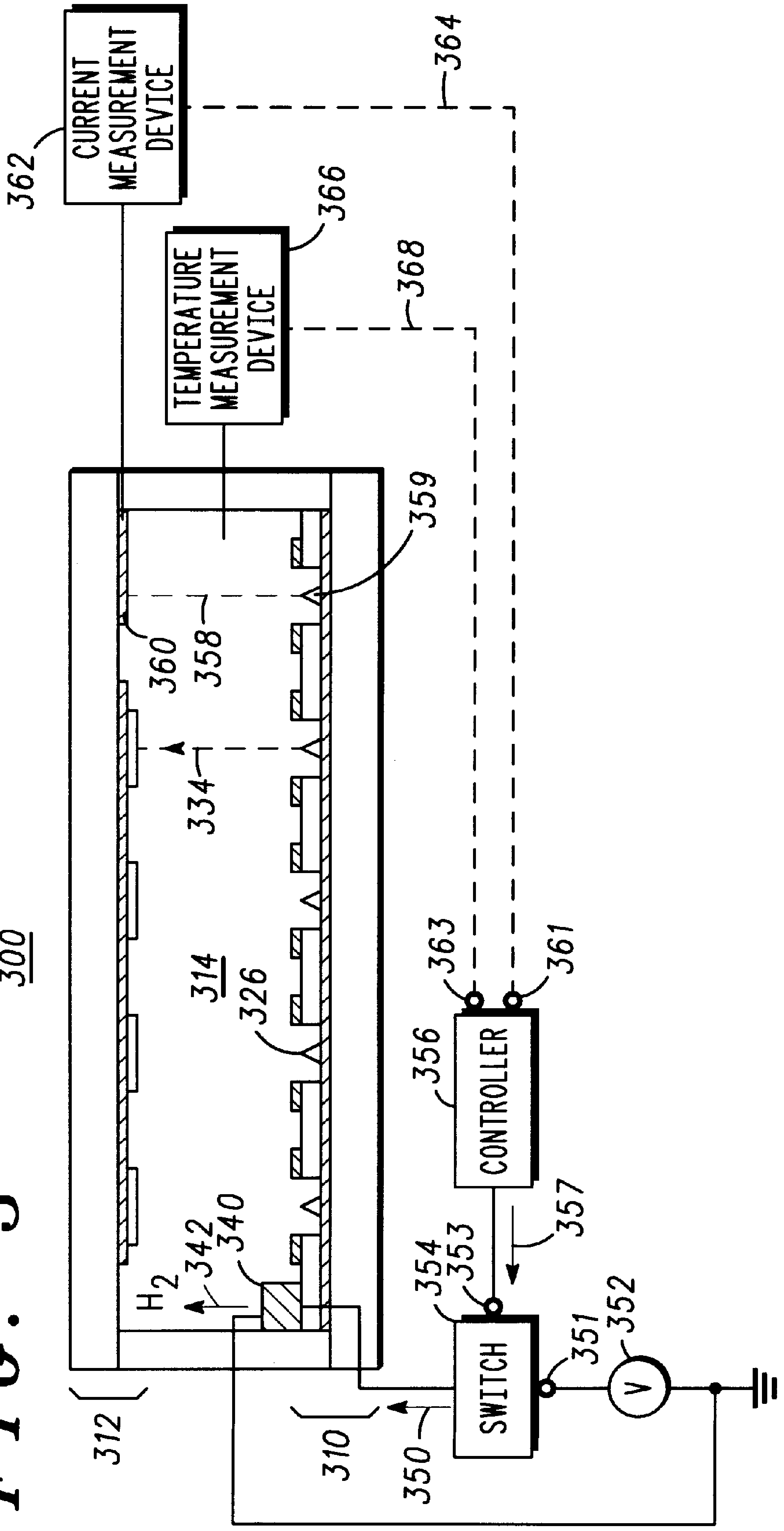
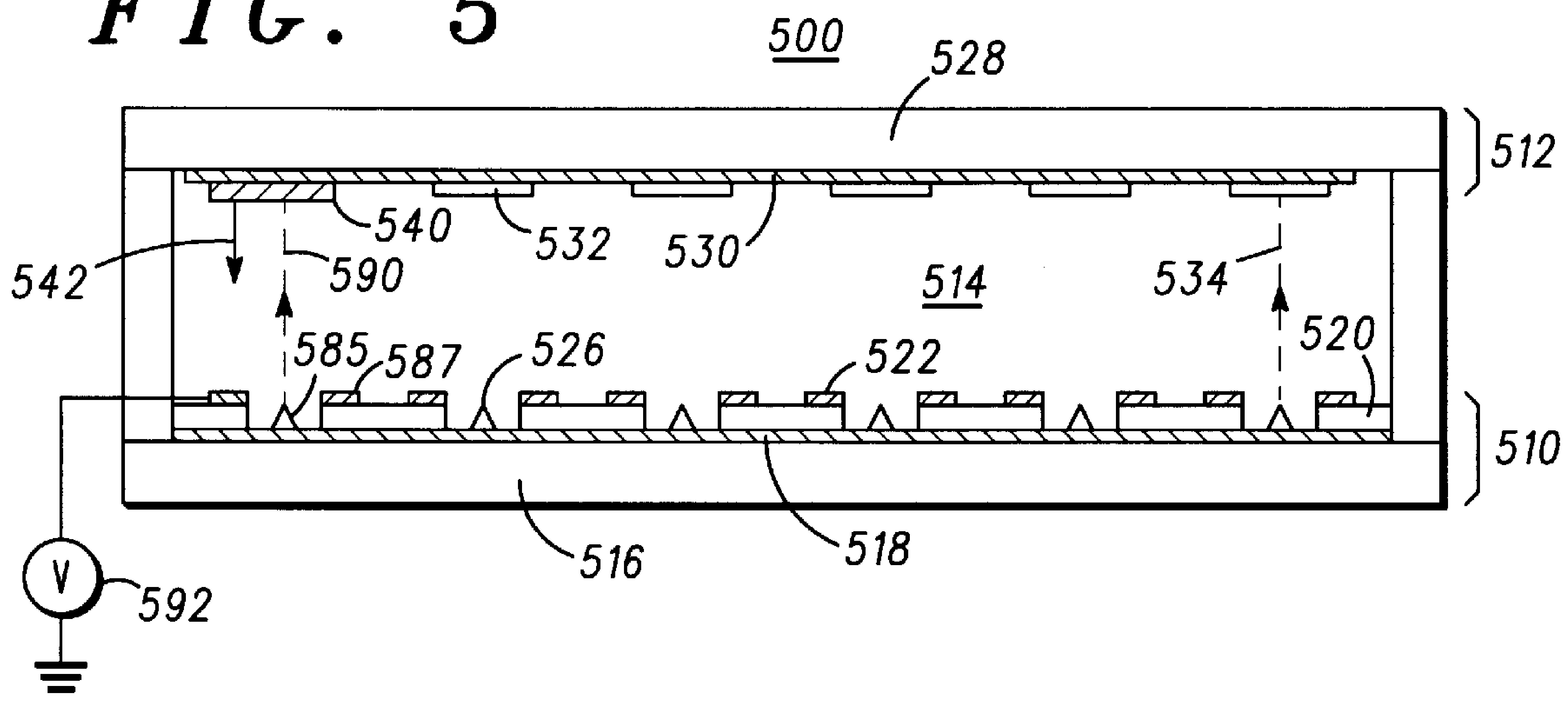

CURRENT MEASUREMENT DEVICE
362
364
TEMPERATURE MEASUREMENT DEVICE
366
368
359
360
358
334
300
314
326
363
361
CONTROLLER
356
357
354
353
340
342
H_2
SWITCH
351
V
352
350
310
312

FIG. 3

FIG. 5


500
528
512
540
532
530
542
590
514
534
585
587
526
522
520
510
516
518
V
592

METHOD FOR IN SITU CLEANING OF ELECTRON EMITTERS IN A FIELD EMISSION DEVICE

REFERENCE TO RELATED APPLICATION

Related subject matter is disclosed in a co-pending, commonly assigned patent application entitled "Field Emission Device Having Means for in Situ Feeding of Hydrogen", attorney docket number FD97060, filed on even date herewith.

FIELD OF THE INVENTION

The present invention pertains to the area of field emission devices and, more particularly, to methods for cleaning and conditioning electron emitters in a field emission device.

BACKGROUND OF THE INVENTION

A typical field emission device contains electron emitters, such as Spindt tips, which are made from an electron-emissive metal, such as molybdenum. These electron emitters are susceptible to surface contamination by oxygen-containing and carbon-containing species. The surface oxygen and carbon have deleterious effects on the electron emission properties of the electron emitters. In particular, the presence of oxygen and carbon at the emissive surface increases the surface work function of the electron emitters. That is, a bigger electric field is required to extract electrons therefrom due to the contamination. Surface contaminants also result in emission current instability and reduced device lifetime.

Metal field emission tips have been employed in field emission electron and ion microscopy, scanning tunneling microscopy, etc. It is known to remove surface contaminants from electron emitters in these microscopy systems by employing high temperature (greater than 2000°K) flashing. However, field emission arrays often include glass substrates upon which the electron emitters are formed. These glass substrates have temperature tolerances upwards of 700–800°K. Thus, high temperature cleaning procedures cannot be used for decontaminating field emission electron emitters formed on glass substrates.

Furthermore, the contamination of field emission electron emitters occurs throughout the life of the field emission device. Contaminant gaseous species are introduced into the vacuum of the field emission device by outgassing from surfaces, by electron-stimulated desorption from the phosphors and other surfaces that are exposed to field emitted electrons, by small leaks in the packaging elements, etc.

In order to maintain constant emission characteristics over the life of the device, it is desirable that emitter surface contaminants be removed throughout the life of the device. It is also desirable that this cleaning process be continuous over the life of the device or be performed periodically at a frequency that is sufficient to prevent appreciable deterioration of emission characteristics. However, field emission devices typically have no convenient means for introducing cleaning agents into the device subsequent to the vacuum sealing of the device package.

Accordingly, there exists a need for a method for in situ decontamination of electron emitters in field emission devices.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a cross-sectional view of a first embodiment of a field emission device useful for performing steps of a method in accordance with the invention;

FIG. **2** is a cross-sectional view of a second embodiment of a field emission device useful for performing steps of a method in accordance with the invention;

FIG. **3** is a cross-sectional view of a third embodiment of a field emission device useful for performing steps of a method in accordance with the invention and includes a block diagram of a configuration for controlling the rate of hydrogen evolution from a hydrogen source in accordance with the invention;

FIG. **4** is a cross-sectional view of a fourth embodiment of a field emission device useful for performing steps of a method in accordance with the invention and includes a block digram of a configuration for controlling the rate of hydrogen evolution from a hydrogen source; and

FIG. **5** is a cross-sectional view of a fifth embodiment of a field emission device useful for performing steps of a method in accordance with the invention.

It will be appreciated that for simplicity and clarity of illustration, elements shown in the FIGURES have not necessarily been drawn to scale. For example, the dimensions of some of the elements are exaggerated relative to each other. Further, where considered appropriate, reference numerals have been repeated among the FIGURES to indicate corresponding elements.

DESCRIPTION

The invention is for a method for in situ cleaning of electron emitters in a field emission device. The method of the invention includes the steps of providing hydrogen gas within the device during the operational life of the device and, thereafter, causing the electron emitters of the field emission device to emit electrons. These electrons interact with the hydrogen gas to form hydrogen free radicals, which are useful for cleaning and conditioning the surfaces of the electron emitters. The decontaminated emissive surfaces provide stable emission current during the operational life of the device. The method of the invention further includes the step of providing within the field emission device hydrogen gas at a rate/frequency sufficient to maintain the surfaces of the electron emitters free of contaminants and thereby maintain stable electron emission over the life of the device.

The field emission devices described herein are directed to field emission display devices having triode configurations and employing Spindt tip electron emitters. However, the scope of the invention is not intended to be limited to display devices, to devices having a triode configuration, nor to devices having Spindt tip electron emitters. In general, the invention can be embodied in a vacuum device that employs field emission electron emitters, such as Spindt tips, edge emitters, wedge emitters, surface conduction emitters, and the like, which are made from a material that can be cleaned/decontaminated using hydrogen free-radicals. Also, the invention can be embodied in a field emission device having a diode configuration or a configuration having greater than three electrodes.

FIG. **1** is a cross-sectional view of a first embodiment of a field emission device (FED) **100** useful for performing steps of a method for in situ cleaning of a plurality of electron emitters **126** in accordance with the invention. FED **100** is an operational device. That is, FED **100** has the operational configuration that is intended for its functional life. FED **100** is evacuated, and the device package components are hermetically sealed. The method of the invention is useful for providing hydrogen gas within FED **100** at a time during the operational life of FED **100**, subsequent to its evacuation and sealing. This allows for in situ cleaning of electron emitters **126**.

FED **100** includes a cathode plate **110**, which is spaced from an anode plate **112** to define an interspace region **114** therebetween. Cathode plate **110** includes a plurality of electron emitters **126**. In general, during the operation of FED **100**, electrons, indicated by a dashed line **134** in FIG. **1**, are emitted by electron emitters **126** and are subsequently collected at anode plate **112**.

Cathode plate **110** includes a substrate **116**, which can be made from glass, silicon, or some other hard, dielectric material. Upon substrate **116** is disposed a plurality of cathodes **118**, which are electrodes made from a conductor, such as molybdenum, aluminum, and the like. A dielectric layer **120** is disposed on cathodes **118** and defines a plurality of emitter wells **124**. Electron emitters **126** are disposed one each in emitter wells **124**. In the embodiment of FIG. **1**, electron emitters **126** include Spindt tips. Electron emitters **126** are made from a field emissive material. Exemplary field emissive materials include molybdenum, niobium, hafnium, tungsten, iridium, silicon, diamond-like carbon, and the like. In general, the field emissive material can be induced to emit electrons by the application of an electric field of appropriate strength. Also, the field emissive material can be conditioned/cleaned using hydrogen free radicals, which include atomic hydrogen and hydrogen ions.

A plurality of gate extraction electrodes **122** is configured upon dielectric layer **120** for selectively addressing electron emitters **126**. Gate extraction electrodes **122** are made from a conductive material, such as molybdenum, aluminum, and the like. Methods for fabricating cathode plate **110** are known to one skilled in the art.

Anode plate **112** includes a transparent substrate **128** made from a solid, transparent material, such as a glass. An anode **130** is formed on transparent substrate **128**. Anode **130** is made from a transparent, conductive material, such as indium tin oxide. Anode plate **112** further includes a plurality of phosphors **132**, which are made from a cathodoluminescent material.

Between cathode plate **110** and anode plate **112**, at their peripheries, is disposed a frame **136**, which provides standoff therebetween. Frame **136** can be made from a glass and is affixed to cathode plate **110** with a sealant **138**. Sealant **138** can be a frit sealant, indium metal, tin, indium tin alloys, other low melting point metals, and the like. Cathode plate **110**, anode plate **112**, and frame **136** define a device package.

A hydrogen-selective membrane **140** is disposed within a hole **144** defined by frame **136** and anode plate **112**. Hydrogen-selective membrane **140** is made from a refractory metal, such as palladium, nickel, a palladium alloy, a nickel alloy, and the like, which is selectively permeable with respect to hydrogen. Preferably, hydrogen-selective membrane **140** is made from palladium. Hydrogen-selective membrane **140** has a thickness, in the direction of hydrogen diffusion, within a range of 50–500 micrometers. Under the appropriate conditions of temperature and pressure, hydrogen gas is capable of selectively diffusing through hydrogen-selective membrane **140**.

FED **100** can be fabricated by first silk-screening sealant **138** onto transparent substrate **128** at the periphery thereof. Then, hydrogen-selective membrane **140** is disposed on sealant **138**. Refractory metal membranes, having thicknesses greater than about 10 micrometers, are available commercially. Such a refractory metal membrane can be cut into a suitable shape to form hydrogen-selective membrane **140**. The structure is then heated to affix the refractory metal to sealant **138**.

Anode plate **112**, having hydrogen-selective membrane **140** formed thereon, is assembled with cathode plate **110**, having frame **136** affixed thereto, in a vacuum environment, so that a vacuum is realized within interspace region **114**. As illustrated in FIG. **1**, hydrogen-selective membrane **140** is thus disposed in communication with interspace region **114**. That is, hydrogen gas, which is indicated by an arrow **142** in FIG. **1**, that diffuses through hydrogen-selective membrane **140** can subsequently travel into interspace region **114**.

Subsequent to the steps of sealing the elements of FED **100** and establishing a vacuum environment therein, the following steps are used to achieve in situ feeding of hydrogen gas into interspace region **114** and in situ cleaning of electron emitters **126**, in accordance with the invention. First, FED **100** is placed in an oven having a hydrogen atmosphere. The hydrogen atmosphere within the oven has a hydrogen partial pressure within a range of milli-Torr to several atmospheres. Then, the temperature within the oven is elevated to within a range of about 273–450°K. In general, the temperature and partial pressure of hydrogen within the hydrogen atmosphere are selected to promote diffusion of hydrogen gas through hydrogen-selective membrane **140**. The hydrogen gas can be controllably provided by manipulating the temperature and the hydrogen pressure external to FED **100** during the diffusion step.

The diffusion of hydrogen into interspace region **114** is performed for a period of time sufficient to provide within interspace region **114** a partial pressure of hydrogen useful for cleaning electron emitters **126**. In accordance with the invention, a partial pressure of hydrogen is achieved within FED **100** that is preferably greater than 10^{-8} Torr, most preferably within a range of 10^{-8}–10^{-5} Torr.

The hydrogen content can be determined by measuring the total pressure within FED **100** prior to the addition of hydrogen and thereafter measuring the total pressure within FED **100** after the addition of hydrogen. If these two measurements are taken at the same temperature, the final hydrogen partial pressure can be derived therefrom by, for example, using the ideal gas law.

In general, clean electron emitters **126** ameliorate the fluctuations in the emission current for a given set of conditions, including operating voltages and temperature. Thus, the level of contamination of electron emitters **126** can be deduced from measured fluctuations in the emission current. Contamination of electron emitters **126** is also reflected by a reduction in the emission current for a given set of emission parameters. In accordance with the invention, a partial pressure of hydrogen is established within interspace region **114** that provides stabilized, constant emission current having fluctuations within a tolerable range. For example, it may be desirable to maintain current fluctuations of less than 0.5% per hour for a given set of conditions.

Subsequent to the step of providing a partial pressure of hydrogen gas within interspace region **114** useful for cleaning electron emitters **126**, electron emitters **126** are activated to emit electrons. Electron emission is realized by applying the appropriate potentials to cathodes **118** and gate extraction electrodes **122**, as is known to one skilled in the art. The emitted electrons are then attracted toward anode **130** by applying thereto an appropriate potential. As they travel across interspace region **114**, the emitted electrons dissociate and ionize the hydrogen molecules present therein, thereby forming hydrogen free radicals within interspace region **114**.

The hydrogen free-radicals, which include hydrogen ions and energetic neutral hydrogen atoms, react with the surfaces of electron emitters **126**, which include surface contaminants, to form volatile hydrides. Exemplary volatile hydrides that may be produced include: H_2O, MoH_x^+ (x=1–3), $MoOH^+$, OH^+, OH, H^+, CH_x^+ , (x=1–4), and the like. These volatile hydrides are then removed from interspace region **114** by gettering material (not shown) present within FED **100**.

It is desired to be understood that the cleaning process is not limited to the removal of contaminants in the form of hydrides alone. The hydrogen free radicals are also capable of catalyzing surface chemical reactions, which produce volatile products that do not include hydrides and which effectively remove surface contaminants.

In accordance with the invention, the steps for cleaning and conditioning electron emitters **126** can be performed shortly after sealing of the device package to remove surface contaminants, native oxides, and process residues. These steps can also be performed after a period of use of FED **100**, thereby reconditioning electron emitters **126** and removing surface contaminants accumulated during the operation of FED **100**. This cleaning procedure is preferably performed periodically over the life of FED **100**, at a frequency sufficient to maintain clean electron emitters **126**. In this manner, stable, constant electron emission is realized over the life of FED **100**.

In general, the means for in situ feeding of hydrogen is disposed in communication with the interspace region of the device package. In the embodiment having a hydrogen-selective membrane, the hydrogen-selective membrane is configured in registration with a hole/gap defined by the device package. Under appropriate conditions of pressure and temperature, this configuration allows hydrogen gas to diffuse from a hydrogen atmosphere external to the field emission device, through the hydrogen-selective membrane, and into the interior of the field emission device.

FIG. **2** is a cross-sectional view of a second embodiment of a field emission device (FED) **200** useful for performing steps of a method in accordance with the invention. FED **200** includes a hydrogen-selective membrane **240**, which is disposed in registration with a hole **244** defined by the device package. Hole **244** is defined by a transparent substrate **228** of an anode plate **212**. Transparent substrate **228** is made from a hard, transparent material, such as a glass, and has affixed thereto an anode **230** and a plurality of phosphors **232**. Hydrogen-selective membrane **240** overlies hole **244**. Hydrogen-selective membrane **240** includes a membrane made from a refractory metal such as palladium, nickel, and the like, which is selectively permeable to hydrogen. The thickness of hydrogen-selective membrane is preferably within a range of 50–500 micrometers.

FED **200** is fabricated by first making a cathode plate **210**, in a manner similar to that described with reference to FIG. **1**. Cathode plate **210** includes a plurality of cathodes **218**, a plurality of electron emitters **226**, and a plurality of gate extraction electrodes **222**. A frame **236** is attached to the periphery of cathode plate **210** by using a frit sealant (not shown). Anode plate **212** is attached to frame **236** to define an interspace region **214**. The step of attaching anode plate **212** can be performed in air because, subsequent to the sealing process, interspace region **214** can be evacuated through hole **244** using a vacuum pump, as is known to one skilled in the art.

Hydrogen-selective membrane **240** is affixed to anode plate **212** by first providing a ring **246** made from an alloy having thermal expansion characteristics that match those of transparent substrate **228**. Hydrogen-selective membrane **240** is brazed to ring **246**, so that it covers the hole defined by ring **246**. Then the hole defined by ring **246** is positioned in registration with hole **244** of transparent substrate **228**. Ring **246** is attached to transparent substrate **228** using a frit sealant **248**. The step of attaching ring **246**, having hydrogen-selective membrane **240** affixed thereto, to transparent substrate **228** is performed subsequent to the evacuation of the device package.

Subsequent to the step of attaching hydrogen-selective membrane **240** to the device package, a hydrogen partial pressure is established within FED **200**, in a manner similar to that described with reference to FIG. **1**. Under appropriate conditions of temperature and pressure, hydrogen gas, which is indicated by an arrow **242** in FIG. **2**, is diffused through hydrogen-selective membrane **240** and travels into interspace region **214**. Within interspace region **214**, the hydrogen gas is converted into hydrogen free radicals by electrons, which are indicated by a dashed line **234** in FIG. **2**, that are emitted by electron emitters **226**.

FIG. **3** is a cross-sectional view of a third embodiment of a field emission device (FED) **300** useful for performing steps of a method in accordance with the invention, and includes a block diagram of means for controlling the rate of hydrogen evolution from a hydrogen source **340**. Similar to FED **100** and FED **200** of FIGS. **1** and **2**, respectively, FED **300** is an operational device. That is, FED **300** has the operational configuration that is intended for its functional life. FED **300** is evacuated, and the device package components are hermetically sealed. The method of the invention is useful for providing hydrogen gas within FED **300** at a time during the operational life of FED **300**, subsequent to its evacuation and sealing. This allows for in situ cleaning of a plurality of electron emitters **326**.

In accordance with the invention, a method for in situ cleaning of electron emitters **326** includes the steps of providing hydrogen source **340** within FED **300**, releasing hydrogen gas from hydrogen source **340**, and, thereafter, forming hydrogen free radicals from the hydrogen gas. The components of the block diagram of FIG. **3** are useful for controllably releasing the hydrogen gas from hydrogen source **340**. In the embodiment of FIG. **3**, the step of controllably releasing hydrogen gas from hydrogen source **340** includes the step of releasing hydrogen gas from hydrogen source **340** in response to a drop below a predetermined value of a test emission current **358** measured at a test electron emitter **359** in FED **300**.

FED **300** has a cathode plate **310** and an anode plate **312**, which define an interspace region **314**. FED **300** further includes hydrogen source **340**, which is disposed within interspace region **314**. Hydrogen source **340** includes a solid member made from a refractory metal, such as palladium, nickel, a palladium alloy, a nickel alloy, and the like. Preferably, hydrogen source **340** is made from palladium. Hydrogen source **340** is secured to one of the surfaces defining interspace region **314** by a convenient method, such as by using a frit sealant or mechanical means.

Hydrogen source **340** contains hydrogen. In accordance with the invention, hydrogen is provided within hydrogen source **340** by first placing the metallic member in an oven having a hydrogen atmosphere. The temperature in the oven is elevated to induce the diffusion of hydrogen gas into the metallic member. After a sufficient amount of hydrogen has been diffused into the metallic member, the metallic member is cooled, thereby entrapping the hydrogen contained therein.

In accordance with the invention, electron emitters **326** are cleaned and conditioned by first controllably releasing hydrogen gas, which is indicated by an arrow **342** in FIG. **3**, from hydrogen source **340**. The rate/frequency of hydrogen evolution from hydrogen source **340** is controlled so as to provide within interspace region **314** a partial pressure of hydrogen that is useful for maintaining a stable emission current. A dashed line **334** in FIG. **3** indicates the emission current.

The step of releasing hydrogen gas from hydrogen source **340** includes the step of heating hydrogen source **340**. Hydrogen source **340** can be heated by passing a current directly through hydrogen source **340**. Alternatively, hydrogen source **340** can be heated by providing a heating element, such as a resistive wire, and providing thermal contact between hydrogen source **340** and the heating element. Subsequent to the step of heating hydrogen source **340**, hydrogen free radicals are produced from the hydrogen gas, in the manner described with reference to FIGS. **1** and **2**. Hydrogen source **340** can also be heated by using an infrared laser.

Illustrated in FIG. **3** is a block diagram of a control system useful for controlling the rate of hydrogen evolution from hydrogen source **340** in accordance with the method of the invention. The control system includes a switching circuit **354**, a controller **356**, a temperature measurement device **366**, and a current measurement device **362**.

Controller **356** controls test emission current **358** that is emitted by test electron emitter **359**. The characteristics of test emission current **358** are representative of the characteristics of the emission currents from the remainder of electron emitters **326**. Controller **356** controls test emission current **358** by manipulating the rate of hydrogen evolution from hydrogen source **340** in response to a first signal **364** from current measurement device **362** and a second signal **368** from temperature measurement device **366**.

A current measurement electrode **360** is configured on anode plate **312** to receive test emission current **358**. Current measurement device **362** is connected to current measurement electrode **360** for measuring test emission current **358**. Current measurement device **362** transmits first signal **364**, which is related to test emission current **358**, to a first input terminal **361** of controller **356**.

Temperature measurement device **366** measures a temperature within interspace region **314** and transmits second signal **368**, which is related to the temperature, to a second input terminal **363** of controller **356**. The value of the emission current is dependent, in part, upon temperature. Controller **356** corrects for this temperature dependence when determining the status of the emission current. When the corrected value of the emission current drops below a predetermined level, the controller transmits a control signal **357** to a first input terminal **353** of switching circuit **354**.

Switching circuit **354** is responsive to control signal **357**. Switching circuit **354** has an output that is connected to hydrogen source **340** for transmitting an activation current **350** thereto. In general, switching circuit **354** transmits activation current **350** to hydrogen source **340** when the corrected emission current drops below a predetermined value due to surface contamination of electron emitters **326**. In the embodiment of FIG. **3**, a voltage source **352** is connected to a second input terminal **351** of switching circuit **354**. Voltage source **352** can be included in the power supply of FED **300**.

Due to the heating of hydrogen source **340**, the temperature within FED **300** may increase. It is desired to maintain the temperature within FED **300** below that which results in an excessive, catastrophic emission current at electron emitters **326**. Controller **356** is designed to cease heating hydrogen source **340** when the temperature measured by temperature measurement device **366** reaches an upper limit. In this manner, the emission current is prevented from attaining a catastrophic level due to overheating within FED **300** caused by the heating of hydrogen source **340**.

FIG. **4** is a cross-sectional view of a fourth embodiment of a field emission device (FED) **400** useful for performing steps of a method in accordance with the invention, and includes a block diagram of means for controlling the rate of hydrogen evolution from hydrogen source **340**. In the method for in situ cleaning of electron emitters **326** of FED **400**, the step of controllably releasing hydrogen gas from hydrogen source **340** includes the step of releasing hydrogen gas in response to the activation of FED **400**. In this manner, the rate of cleaning of electron emitters **326** is responsive to the extent of use of FED **400**.

FED **400** includes anode plate **112** and cathode plate **310**, which define an interspace region **414**. In the embodiment of FIG. **4**, the system for controlling the rate of hydrogen evolution from hydrogen source **340** includes a current source **474** and an N-counter circuit **472**.

FED **400** has a start-up circuit **470**, which initially activates the device. Start-up circuit **470** is coupled to cathode plate **310** and anode plate **112** (connections not shown) and provides the proper operating voltage for powering FED **400**. When start-up circuit **470** is activated, it transmits a start-up signal **480** to an input terminal **476** of N-counter circuit **472**. Start-up signal **480** triggers a counter. When the counter reaches N, N-counter circuit **472** transmits from an output terminal **477** an activation signal **478**. Activation signal **478** is received at an input terminal **471** of current source **474**.

Current source **474** has an output terminal **473** that is connected to hydrogen source **340**. Upon receipt of activation signal **478**, current source **474** transmits an activation current **475** to hydrogen source **340**, resulting in evolution of hydrogen gas from hydrogen source **340**.

The amount of current sent to hydrogen source **340** each time N-counter reaches N and the value of N depend upon factors such as the size of FED **400** and the anticipated extent of contamination during a given period of use of FED **400**. The latter factor depends in part upon the nature of the materials present within FED **400**. For example, different materials may generate contaminants at different rates.

In accordance with the invention, the step of controllably releasing hydrogen gas from a hydrogen source can include the step of periodically releasing hydrogen gas from the hydrogen source. A field emission device useful for performing periodic hydrogen emissions has a configuration similar to that depicted in FIG. **4** and includes a control system having a timer circuit. In this embodiment, a current source is connected to the hydrogen source; however, the timer circuit is substituted for the N-counter circuit. The timer circuit generates a periodic activation signal, which is transmitted to the current source. In this manner, a predetermined amount of current can be periodically transmitted to the hydrogen source at predetermined intervals. For example, hydrogen evolution can be provided once per month using this configuration.

The step of maintaining within the field emission device a partial pressure of hydrogen gas sufficient to maintain stable electron emission can also include the step of maintaining within the field emission device a partial pressure of hydrogen greater than 10^{-8} Torr, preferably within a range of 10^{-8}–10^{-5} Torr. A field emission device useful for performing this step includes a feedback control system, similar to that of FIG. **3**, for controlling the hydrogen partial pressure. For example, this feedback control system can include a device for measuring the total pressure within the device. A change in the total pressure can be attributable to a change in the partial pressure of hydrogen. The pressure measurement device transmits a signal, which is related to total pressure, to a controller. When the pressure drops below a predetermined value, the controller transmits a control signal to a switch or current source, to generate an activation current. The activation current is transmitted to the hydrogen source to cause hydrogen evolution therefrom.

FIG. **5** is a cross-sectional view of a fifth embodiment of a field emission device (FED) **500** useful for performing steps of a method in accordance with the invention. The introduction of hydrogen, which is indicated by an arrow **542**, into an interspace region **514** of FED **500** is realized by an electron-stimulated hydrogen desorption process. Specifically, the step of releasing hydrogen gas from a hydrogen source **540** includes the step of impinging electrons, which are indicated by a dashed line **590**, onto hydrogen source **540**. The rate of hydrogen evolution depends upon the density and energy of the impinging electron beam, and no thermal heating of hydrogen source **540** is required.

In the embodiment of FIG. **5**, an activation electron emitter **585** provides the impinging electron beam. Hydrogen source **540** opposes activation electron emitter **585**. Hydrogen source **540** is made in the manner described with reference to hydrogen source **340** of FIGS. **3** and **4**. A cathode plate **510** includes activation electron emitter **585**, which is one of a plurality of electron emitters **526** disposed within emitter wells defined by a dielectric layer **520**. Electron emitters **526** are connected to a plurality of cathodes **518**, which are disposed on a substrate **516**.

An activation gate extraction electrode **587** is disposed proximate to activation electron emitter **585** and is coupled to a voltage source **592**. Activation gate extraction electrode **587** is controlled independently from a plurality of gate extraction electrodes **522**, which are used to selectively address those of electron emitters **526** that oppose a plurality of phosphors **532**.

Selectively addressing activation electron emitter **585** controllably provides the hydrogen gas. Voltage source **592** is used to selectively apply an extraction voltage at activation gate extraction electrode **587**. When hydrogen evolution from hydrogen source **540** is desired, voltage source **592** is used to apply the extraction voltage to activation gate extraction electrode **587**, thereby realizing electron emission from activation electron emitter **585**. When no hydrogen evolution from hydrogen source **540** is desired, voltage source **592** is used to apply a voltage that does not result in electron emission from activation electron emitter **585**. The output voltage of voltage source **592** can be manipulated using one of a number of useful control methods, such as those described with reference to FIGS. **3** and **4**.

An electron-attracting voltage is provided at hydrogen source **540** by a voltage source (not shown), so that the electrons from activation electron emitter **585** are attracted to and collected at hydrogen source **540**. In the embodiment of FIG. **5**, hydrogen source **540** is disposed on an anode plate **512**. Anode plate **512** includes a transparent substrate **528**, upon which is formed an anode **530**. Hydrogen source **540** is connected to anode **530**, to which the electron-attracting voltage is applied. Phosphors **532** are also configured on anode **530**. The electrons collected at hydrogen source **540** stimulate hydrogen evolution therefrom. The hydrogen thus evolved is then ionized by electrons within interspace region **514**, including the electrons, which are generally indicated by a dashed line **534**, directed toward phosphors **532**.

In an alternative embodiment, the hydrogen source is not coupled to the anode. Rather, the hydrogen source is coupled to an independent voltage source, so that the voltage at the hydrogen source can be manipulated independently from the voltage at the phosphors. In this particular embodiment, the electrons for use for hydrogen evolution can be provided by any of the electron emitters within the device. The emitted electrons are directed toward the hydrogen source by selectively biasing it to attract the electrons. For example, subsequent to the sealing and evacuation of the device, some or all of the electron emitters are caused to emit electrons. Simultaneously, a positive, attracting voltage is selectively applied to the hydrogen source. After the decontamination steps are completed, the positive, attracting voltage is removed from the hydrogen source. Any subsequently emitted electrons can be directed toward the phosphors by selectively applying a positive, attracting voltage to the phosphors.

In summary, the invention is for a method for in situ cleaning of electron emitters in a field emission device. The method of the invention includes steps for controllably providing hydrogen gas within the field emission device and, thereafter, forming hydrogen free radicals from the hydrogen gas. The hydrogen free radicals are useful for cleaning the electron emitters. The steps of the method of the invention can be performed at any time subsequent to the vacuum sealing of the device package. Further, the hydrogen gas is controllably introduced at a rate/frequency sufficient to remove surface contaminants and maintain clean electron emitters, thereby realizing stable electron emission over the life of the device.

While we have shown and described specific embodiments of the present invention, further modifications and improvements will occur to those skilled in the art. We desire it to be understood, therefore, that this invention is not limited to the particular forms shown, and we intend in the appended claims to cover all modifications that do not depart from the spirit and scope of this invention.

We claim:

1. A method for in situ cleaning of electron emitters in a field emission device comprising the steps of:

introducing hydrogen gas into the field emission device at a time subsequent to sealing of the field emission device; and

thereafter, forming hydrogen free radicals from the hydrogen gas.

2. The method for in situ cleaning of electron emitters as claimed in claim **1**, wherein the step of introducing hydrogen gas into the field emission device includes the step of controllably introducing hydrogen gas within the field emission device.

3. The method for in situ cleaning of electron emitters as claimed in claim **2**, wherein the step of controllably introducing hydrogen gas into the field emission device includes the step of periodically introducing hydrogen gas within the field emission device.

4. The method for in situ cleaning of electron emitters as claimed in claim **1**, wherein the step of forming hydrogen free radicals from the hydrogen gas includes the step of emitting electrons from the electron emitters.

5. The method for in situ cleaning of electron emitters as claimed in claim **1**, wherein the step of introducing hydrogen gas into the field emission device includes the step of diffusing hydrogen gas through a hydrogen-selective membrane.

6. The method for in situ cleaning of electron emitters as claimed in claim **5**, wherein the step of diffusing hydrogen gas through a hydrogen-selective membrane includes the step of diffusing hydrogen gas through a hydrogen-selective membrane disposed in registration with a hole defined by the device package.

7. A method for in situ cleaning of electron emitters in a field emission device having an evacuated interspace region, the method comprising the steps of:

providing a hydrogen source within the evacuated interspace region of the field emission device;

releasing hydrogen gas from the hydrogen source; and

thereafter, forming hydrogen free radicals from the hydrogen gas.

8. The method for in situ cleaning of electron emitters as claimed in claim **7**, wherein the step of providing a hydrogen source includes the steps of providing a member made from a refractory metal, heating the member in a hydrogen atmosphere, and thereafter cooling the member, thereby entrapping hydrogen within the member.

9. The method for in situ cleaning of electron emitters as claimed in claim **8**, wherein the step of providing a member made from a refractory metal includes the step of providing a member made from palladium.

10. The method for in situ cleaning of electron emitters as claimed in claim **7**, wherein the step of releasing hydrogen gas from the hydrogen source includes the step of impinging electrons onto the hydrogen source.

11. The method for in situ cleaning of electron emitters as claimed in claim **10**, wherein the step of impinging electrons onto the hydrogen source includes the step of impinging onto the hydrogen source electrons emitted by at least one of the electron emitters.

12. The method for in situ cleaning of electron emitters as claimed in claim **7**, wherein the step of releasing hydrogen gas from the hydrogen source includes the step of heating the hydrogen source.

13. The method for in situ cleaning of electron emitters as claimed in claim **7**, wherein the step of forming hydrogen free radicals from the hydrogen gas includes the step of emitting electrons from the electron emitters.

14. The method for in situ cleaning of electron emitters as claimed in claim **7**, wherein the step of releasing hydrogen gas from the hydrogen source includes the step of controllably releasing hydrogen gas from the hydrogen source.

15. The method for in situ cleaning of electron emitters as claimed in claim **14**, wherein the step of controllably releasing hydrogen gas from the hydrogen source includes the step of releasing hydrogen gas from the hydrogen source in response to activation of the field emission device.

16. The method for in situ cleaning of electron emitters as claimed in claim **14**, wherein the step of controllably releasing hydrogen gas from the hydrogen source includes the step of periodically releasing hydrogen gas from the hydrogen source.

17. The method for in situ cleaning of electron emitters as claimed in claim **14**, wherein the step of controllably releasing hydrogen gas from the hydrogen source includes the step of releasing hydrogen gas from the hydrogen source in response to the drop below a predetermined value of a test emission current measured at a test electron emitter in the field emission device.

18. The method for in situ cleaning of electron emitters as claimed in claim **14**, wherein the step of controllably releasing hydrogen gas from the hydrogen source includes the step of releasing hydrogen gas from the hydrogen source at a rate sufficient to clean the electron emitters and thereby maintain stable electron emission for a given set of conditions within the field emission device.

19. A method for in situ cleaning of electron emitters in a field emission device comprising the steps of:

sealing the field emission device; and

thereafter, adjusting a partial pressure of hydrogen gas within the field emission device in a manner sufficient to maintain stable electron emission having fluctuations within a tolerable range.

20. The method for in situ cleaning of electron emitters as claimed in claim **19**, wherein the step of adjusting a partial pressure of hydrogen gas includes the step of maintaining within the field emission device a partial pressure of hydrogen greater than 10^{-8} Torr.

21. The method for in situ cleaning of electron emitters as claimed in claim **20**, wherein the step of adjusting a partial pressure of hydrogen gas includes the step of maintaining within the field emission device a partial pressure of hydrogen within a range of 10^{-8} to 10^{-5} Torr.

* * * * *